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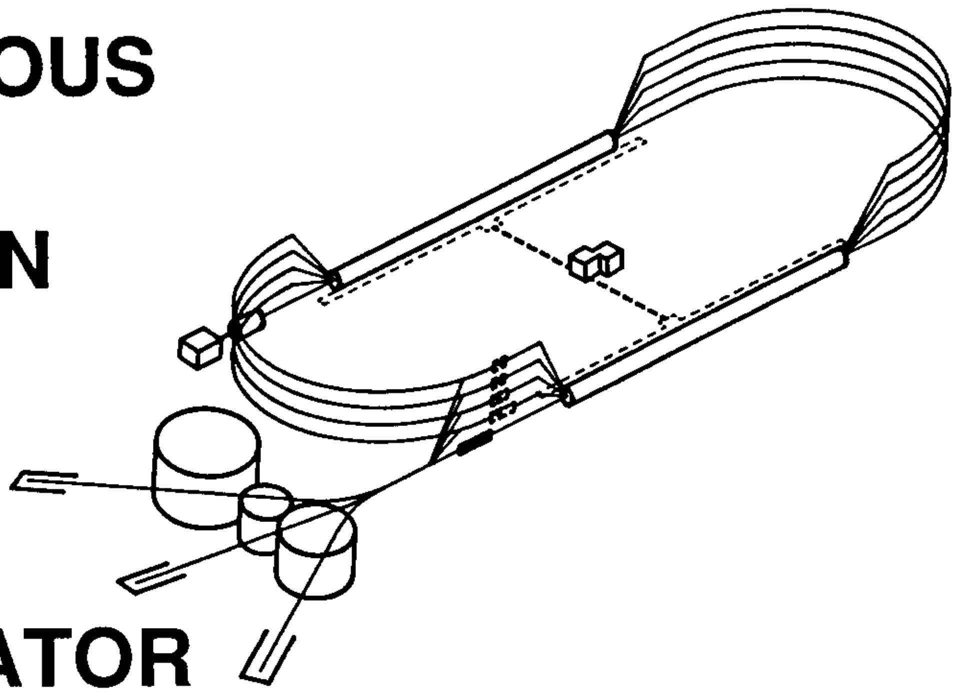

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ABSTRACT

The approaching availability of a high quality, continuous electron beam from the CEBAF accelerator presents the opportunity to explore regimes of free electron laser (FEL) physics and photon production heretofore unapproachable. Using a 3 cm wavelength hybrid wiggler with 200 MeV from the North Linac and a new photoinjector, output powers exceeding 1 kW CW could be achieved at wavelengths from 200 to 700 nm. A simple electromagnetic wiggler utilizing the output of the CEBAF injector could provide an early test of operation and ultimately simultaneous output in the 0.7 to 3 micron range. Details of the design and performance analyses will be discussed.

INTRODUCTION

The CEBAF accelerator will be a 4 GeV, 200 μA CW electron accelerator for basic research in nuclear physics[1]. It achieves continuous operation through the use of superconducting RF cavities operating with helium refrigeration at 2K. The projected electron beam quality and energy spread are excellent with a design edge emittance of 2π nm at 1 GeV and a energy spread of better than 10^{-4}. The machine uses five passes through two antiparallel linacs to achieve full energy. The five-cell superconducting cavities were originally designed at Cornell and are manufactured by Interatom. Processing, assembling the cavities into dewars, and testing is performed at CEBAF. Of the > 110 cavities manufactured to date, all have met the specification for gradient (5 MV/m) and most meet the Q specification of 2.4×10^9 at 5 MeV. In fact, the average gradient is close to 10 MV/m with the best cavities exceeding three times baseline gradient.

The stability and beam quality required by high resolution nuclear scattering experiments are also necessary requirements for short wavelength operation of FELs. With this in mind we have explored the possibility of utilizing the early phases of the CEBAF linac operation for tunable coherent light generation. A natural consequence of the CW nature of the linac is the projected high average power that could be produced. We have explored two possible locations for FELs; one is at the output of the CEBAF Front End where the beam has energies of up to 45 MeV single pass or 85 MeV with a single recirculation. The other is located at the end of the North Linac. Energies up to 445 MeV could be possible. In either case a new injector for the FEL would be required since the FEL requires high peak current for sufficient gain. The new injector in this study is presumed to be a photoinjector with the capability of providing up to 110 A of peak current in a 2 ps micropulse (.23 ncoul) at a normalized RMS emittance of 15 π mmmrad. These pulses would be delivered at the 200th subharmonic of the CEBAF's fundamental frequency of 1497 MHz, 7.485 MHz.

OPERATIONAL LIMITATIONS

Operation of FELs at CEBAF would be subject to several constraints including available RF power, induced wakefields, and, after physics commissioning in 1994, constraints deriving from the need for simultaneous operation of an undegraded electron beam for nuclear physics. An example of this would be beam loading induced energy droop which must remain below a $\Delta E/E$ of 10^{-4}. In this section we briefly explore the most significant of these.

In dedicated FEL operation, the proposed design allows an average current of 1.7 mA to be accelerated using the available 4 kW at reduced gradient. Full current nuclear physics operation at 200 μ A at 4 GeV requires 1 mA (five passes of 200 μA) to be accelerated at full gradient. At 4 kW/cavity only an additional 450 μA can be accelerated, which is equivalent to only a 60 pC bunch charge or 30 A peak current unless a dispersion section is used to compress the pulse length.

There is neither RF power nor RF control bandwidth to compensate for the instantaneous gradient decrease from the high charge bunches at the 200th subharmonic. Due to the high gradient and Q of the superconducting cavity the fractional fundamental voltage droop would be 5×10^{-5} which would act on the nuclear physics pulses which follow (the voltage gradually recovers its original value by the arrival of the 200th micropulse only to receive another high charge load).

An additional 5×10^{-5} of energy jitter could be induced from high-Q HOMs. Using previous estimates of the impedance[2] for bunches of 60 pC the HOM power is conservatively estimated to be

$$P_{hom} = q^2 k_l f = 0.5 \text{ W/cavity}$$

where k_l is the loss factor of the cavity, q is the charge in the bunch and f is the bunch repetition frequency. Since the fundamental mode cooling power is 5.4 W/cavity dissipation in the helium cooled HOM loads should not be a problem.

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1-D PERFORMANCE ESTIMATES

Using the characteristics of the electron beam described above we examined possible operation at two wavelength ranges using the 1-D formula for FEL gain[3]. Although the small signal gain formula cannot correctly predict effects such as performance degradation due to energy spread, emittance, etc., and does not handle saturation or effects on the optical mode, it does serve as a useful figure of merit for comparison of various designs. The actual gain may be expected to be within a factor of a few of such predictions.

Table 1. A summary of the parameters of four wigglers considered in the design study.

Type	Electromagnetic		SmCo/Iron Hybrid	
Configuration	Uniform planar		Planar optical klystron	
Periods	30	30	50 + 400 effective	same
Length (m)	1.5	1.5	2 × 1.5	2 ×1.5
Wavelength (cm)	3	5	3	5
Peak B (kG)	2.1	3.8	5.1	9.4
K	0.4	1.2	1.0	3.1
Gap (cm)	1.0	1.0	1.0	1.0
ΔB/B (%)	0.2	0.2	0.5	0.5

Four wigglers were examined utilizing electromagnetic technology and REC-iron hybrid technology. Their parameters are given in Table 1. None of the wiggler designs is believed to stress the state of the art in any area. Although the UV wiggler is configurable as an optical klystron, no credit has been taken for the enhancement of gain.

Assuming rather short wiggler lengths and optical cavities with 30% outcoupling the output was estimated using 1/2N as the saturation efficiency, where N is the number of wiggler periods. Higher efficiency could be produced by tapering the wiggler[4]. The wavelength performance for the four wigglers in each case is shown in Figure 1a) and 1b) for the IR and UV respectively. The power outputs are considerable, exceeding that available from all tunable and most fixed wavelength lasers by several orders.

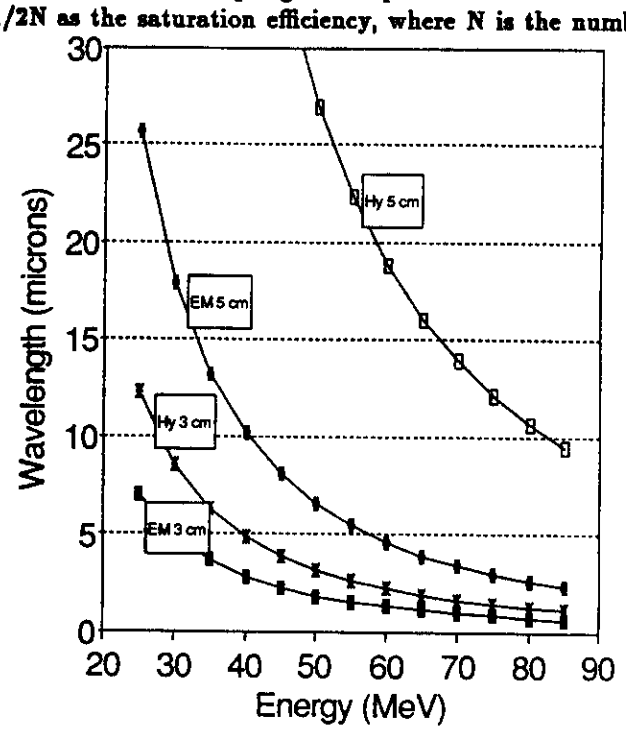

Figure 1a. IR performance of the four wigglers listed in Table 1.

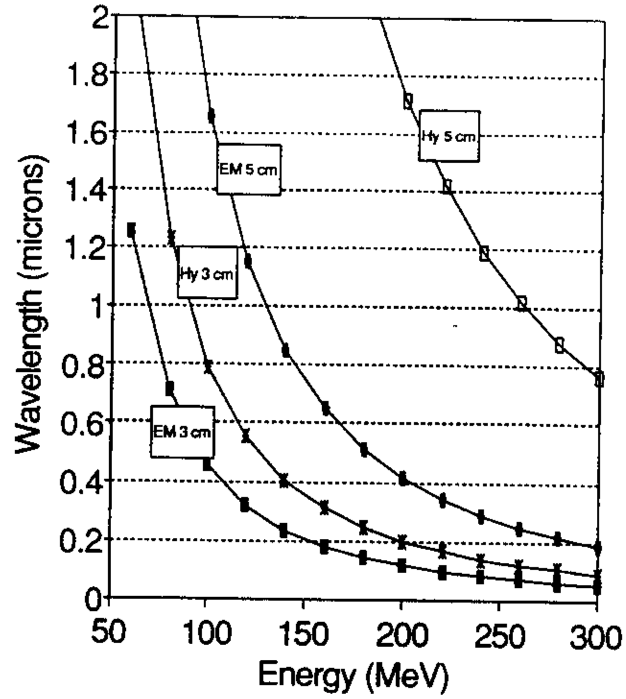

Figure 1b. UV performance of the four wigglers in Table 1.

It is worth noting that the energy and beam quality available is similar to that at VEPP3 which currently holds the world's record for short wavelength FEL lasing[5]. Moreover, the CEBAF peak current (which is proportional to small signal gain) is 20 times higher and optical cavity reflectivities could be comparable. During operation the FEL induces significant growth in energy spread highlighting the potential advantage of a linac configuration over a storage ring: new, unperturbed electrons are used each time.

The optical cavity deserves careful consideration in view of the high optical power predicted. In the IR region sufficient capability exists to manage the high powers with metal mirrors. The long wavelengths give a relative insensitivity to thermally induced distortion. Further, the relatively bright beam gives significant gain estimates in 1-D analytic formulas (Figure 2). The gains are so high in some cases that the performance estimates are significantly in error since they presume slow changes of the optical field and weak interactions with the pondermotive potential well. In addition, during growth of the optical mode to saturation the optical mode can be expected to distort due to gain guiding[6]. This leads to even higher effective gains but mismatch between the optical cavity and the mode during growth to saturation. Such effects would not be expected to hamper operation of a CW system.

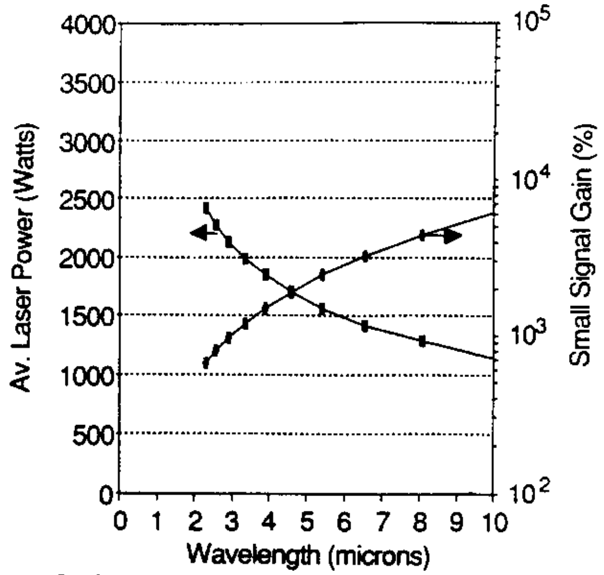

Figure 2. Average output and 1-D small signal gain for the IR FEL under dedicated FEL operation.

In the UV region the longer Rayleigh range and the desire to push operation to as short a wavelength as possible suggests that use of a novel resonator design such as that proposed by Shih, *et al.*,[7] see Figure 3. This resonator has the interesting property that it is extremely insensitive to alignment errors and jitter, permitting the mirrors to be placed very far away from the wiggler. The calculated 1-D optical gain in the UV region is also quite large (Figure 4).

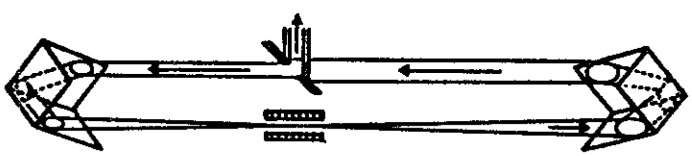

Figure 3. A schematic of the re-imaged retro-reflective ring resonator.[7]

Table 2 shows a possible hardware implementation of such resonators. Virtually all the parameters are achievable with inexpensive, off-the-shelf components with the possible exception of the mirror power loading which is close to the maximum specifications and the sensitivity of the cavity to proper mirror curvature. As shown in Figure 1b the higher energy available at the end of the North Linac yields wavelengths with the proposed wigglers that are shorter than conventional optics can handle. Several

Table 2. Possible resonator design parameters.

Outcoupling (%)	30	20
Length (m)	20.04	60.12
Rayleigh range (m)	0.75	1.5
Radi of Curve (m)	10.076	30.079
w_0 (mm) @ λ (nm)	0.66 @ 1850	0.32 @ 210
Fresnel #	8.5	25.5
Configuration	Near concentric	Re-imaged retro ring
Outcoupling	Hole/Partial refl.	Scraper
Substrate	Copper/ZnSe	Sapphire

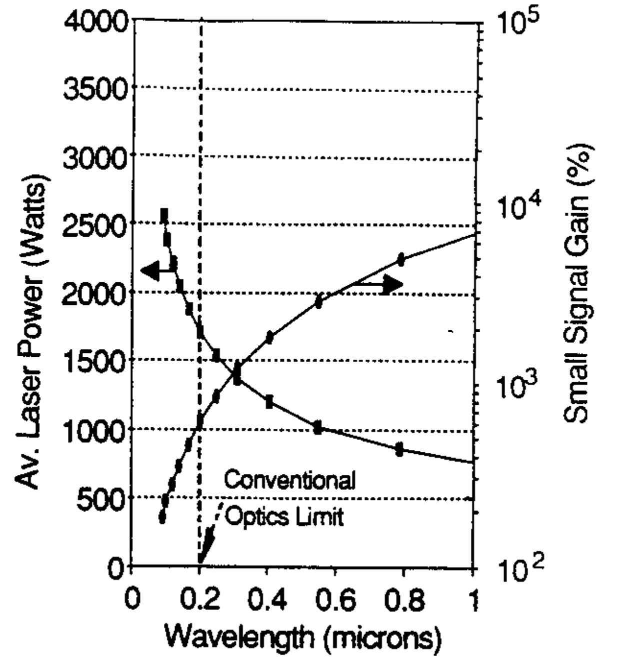

Figure 4. Average laser output and 1-D small signal gain for the UV FEL. With simultaneous nuclear physics operation the FEL performance would be reduced due to lower current. Mirror technology limits operation below about 200 nm.

resonators/mirrors have been proposed for this region[8]. Further research will be required to determine if any are practical for use with the proposed high power UV FEL.

SUMMARY

In summary, we have performed conceptual studies of a pair of FELs located at the output of the Front End and North Linac of the CEBAF accelerator. The high average beam power coupled with the superior electron beam quality produced by the linac yield projections of tunable output power that substantially exceed existing and most proposed sources. The tolerances for most FEL components are not severe but the high optical power requires careful consideration and, perhaps, special optical cavity arrangements and mirror designs.

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